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Effect of Confining Layers of Steel Straps Confined High-Strength Concrete Cylinder under Uniaxial Cyclic Compression

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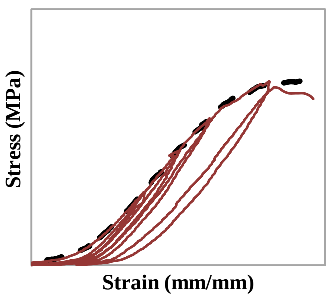
Graphical abstract



Abstract

The remarkable advantages and promising increment in concrete ultimate capacity as well as ductility by using steel straps as lateral confinement has brought the steel strapping tensioning technique (SSTT) as one of the most affordable confining technique in market. A number of studies have been reported the behaviour of SSTT-confined concrete under uniaxial monotonic compression loading but none of any study addressed the uniaxial cyclic response of such confinement. In this paper, twenty-one high-strength concrete cylinder specimens with diameter of 150 mm and 300 mm in height were cast, laterally pre-tensioned with steel strap in different confining layers and tested to failure under uniaxial cyclic and monotonic compression loading. A number of conclusions to be drawn from experimental results including the tangential validation of stress-strain curve for uniaxial monotonic and cyclic loading, independency of plastic strain to the amount of confining layers, the disagreement of uniqueness concept on the repeated uniaxial unloading and reloading cycles, and the promising effect of confining layers and loading patterns to the ultimate capacity of SSTT confinement. A plastic strain model is proposed and compared with existing plastic strain models. The result proved that SSTT confinement able to secure the lowest plastic strain among the others existing confinement method.

Keywords: Lateral confinement; steel straps, confining layers, uniaxial cyclic loading, stress-strain behaviour

Abstrak

Penggunaan lilitan keluli sebagai satu teknik lilitan sisi telah dibukti mempunyai kelebihan yang banyak serta boleh meningkatan kekuatan mampatan dan kemuluran konkrit dengan efektif. Ini telah menjadikan teknik lilitan sisi keluli (SSTT) sebagai salah satu teknik yang berkos-efektif di pasaran. Kebanyakan kajian melaporkan kelakuan konkrit berlilitan SSTT di bawah beban mampatan paksi *monotonic* dan masih tiada kajian dilakukan untuk tindak balas mampatan kitaran di bawan beban mampatan paksi *cyclic*. Sebanyak 21 konkrit silinder kekuatan tinggi berdiameter 150 mm dan berketinggian 300 mm disediakan dan dipra-tegang dengan lapisan lilitan keluli yang berbeza dan diuji dengan beban mamptan paksi *monotonic* and *cyclic* sehingga silider konkrit mengalami kegagalan. Beberapa kesimpulan boleh dibuat termasuk pengesahan lengkung tegasan-terikan antara beban mampatan *monotonic* dan *cyclic*, ketidak-gantungan terikan plastik kepada bilangan lapisan lilitan keluli, ketidak-setujuan atas konsep unik pada beban mampatan *cyclic* yang berulang-ulang kitarannya, dan kesan positif lapisan lilitan keluli dan corak beban mampatan kepada kekuatan mampatan konkrit berlilitan SSTT. Satu model terikan plastik telah dicadangkan dan dibandingkan dengan model terikan plastik yang lain, dan hasil perbandingan telah membuktikan bahawa lilitan SSTT mempunyai terikan plastik yang paling rendah di antara model terikan plastik yang lain.

Kata kunci: Lilitan sisi; lilitan keluli; lapisan lilitan; beban mampatan paksi cyclic; hubungan tegasan-terikan

1.0 INTRODUCTION

The application of steel strapping tensioning technique (SSTT) in enhancing the ultimate strength and ductility of new and existing concrete structures has been recognized in several research studies [1–10]. The significant advantages of it mechanical properties enhancement, low cost, ease to operate, time saving, less interruption of the use of structure during application and less depending on experienced worker by using steel straps with lateral pre-tensioning stress in layers has brought SSTT as of the most affordable confining technique in market, especially applying onto high-strength concrete which naturally behaved brittle and low ductility when loaded to ultimate capacity. The confining ratio plays an important parameter in the ultimate capacity and ductility enhancement as well as stress-strain behaviour in SSTT confinement. It is also the main focus of investigation for most of the related existing researches [3, 5–10]. Moghaddam *et al*. [5–9] studied the effect of confining ratio of steel straps to the stress-strain behaviour of SSTT confined concrete, which including the number of layer of steel straps and spacing between each steel straps. A strong and linear relationship between the confining ratios and ultimate capacity and ductility has been concluded in the study. An empirical models in the function of confining ratios were proposed for design use. Frangou *et al*. [10] also found out a reverse relationship between the spacing of each steel straps and stress-strain behaviour of the confinement, where the smaller the spacing between steel straps (also equalised to higher confining ratio), the higher the ultimate capacity can be archived. Besides, a close and increasing linear relationship between confining ratio and compressive strength of SSTT confinement on high-strength concrete has been concluded by Awang *et al*. [3], where a simple strength model equation for SSTT confinement was proposed. Hence, from the literature studies, most of the existing researches tested the SSTT confinement with uniaxial monotonic compression load and there is no investigation been carried out yet to investigate the cyclic responses of SSTT confinement under uniaxial cyclic compression load. The lacking of test data of these confinement under such loading sequence prompts the need of more quantitative experimental investigations on the influence of confining ratios, for the development of theoretical models. In this paper the results of uniaxial cyclic and monotonic compression load tests on twenty-one SSTT confined high-strength concrete cylinder specimens with different confining ratios are presented and the behaviour of the confined specimens was examined and discussed through several different aspects of cyclic behaviour.

■2.0 EXPERIMENTAL WORK

2.1 Material and Specimen Preparation

A set of twenty-one high-strength concrete cylinder specimens having dimension of 150 mm and 300 mm in diameter and height respectively, were prepared. The testing parameters in this study were primarily dealt with the confining ratio of SSTT confinement and the testing load patterns (uniaxial monotonic and cyclic compression). The cyclic responses of SSTT confinement under such testing load patterns were examined and investigated in this study. Each of the cylinder specimens were not reinforced longitudinally with steel bar. The spacing between each confined steel straps were fixed at 15 mm along the center of specimens and 7.5 mm at the two end regions to provide sufficient confinement, as illustrated in Figure 1. This would greatly reduce the possibility of pre-mature failure at the two end sections of the cylinder specimens.

Table 1 shows the mix design proportions used to cast high-strength concrete in this study. The target cylinder compressive strength at 28 days was 60 MPa and the actual average cylinder strengths at testing day, which was about 120 days after casting, were 59.18 MPa. All specimens were prepared in a batch of casting, and went through wet curing for 28 days before proceed to SSTT confinement procedure.

The wet curing process was stopped right after 28 days and all the cylinder specimens were laterally pre-tensioned with prescribed layers of steel straps as shown in Table 2 except unconfined cylinder specimens which were assigned as control specimens in this study. The confinement method was fully followed the SSTT confinement method designed by Awang *et al*. and Hoong-Pin *et al*. [1–4] by using tensioner. It is recommended to confined up to 30% of the tensile yield strength of the steel straps as to effectively mobilize the confining material from the initial state of loading application [8].

During this study, all the twenty-one cylinder specimens were equally assigned into seven groups testing as presented in Table 2. The annotation of C60-C-M was assigned for control specimens, C60S15-2FT-M, C60S15-4FT-M for specimens pre-tensioned with two and four layers of steel straps, and tested under uniaxial monotonic compression load test (denoted as “M”), while C60S15-2FT-1C, C60S15-4FT-1C for specimens pre-tensioned with two and four layers of steel straps, tested under uniaxial single cyclic compression load test, respectively. While for annotation of C60S15-2FT-3C and C60S15-4FT-3C indicating the specimens pre-tensioned with two and four layers of steel straps, tested under uniaxial three cyclic compression load test, respectively. The notation of “15” indicating the spacing between steel straps along the specimens. To ensure that the specimens were uniformly loaded during testing, it is important to make sure that the top and bottom surface of the specimens were paralleled. So, the specimens had to be cast horizontally on a levelled surface.

Figure 1 SSTT-confined high-strength concrete specimens

Table 1 High-strength concrete mix design

Materials	Type	Quantity
Cement (kg/m^3)	Type I OPC	550
Sand (kg/m^3)	River sand	885
Aggregate (kg/m^3)	Maximum size 12mm	957
Superplasticizer (mL)	Glenium ACE388 (RM)	0.75% of 100 kg cement
Water (kg/m^3)	Pipe water	190
Water/Cement ratio	-	0.35

Table 2 Specimens and testing properties

Specimen notation	Number of steel strap layers	Testing load patterns
C60-C-M	-	M
C60S15-2FT-M	2	M
C60S15-2FT-1C	2	1C
C60S15-2FT-3C	2	3C
C60S15-4FT-M	4	M
C60S15-4FT-1C	4	1C
C60S15-4FT-3C	4	3C

2.2 Testing Setup

The load tests were conducted using TINIUS OLSEN Super "L" Universal Testing Machine which has the capacity of 3 MN in Geotechnics Laboratory, Faculty of Civil Engineering and the load tests were based on displacement-controlled loading with constant loading rate of 0.4 mm/min. The overall view of the specimen set up and diagram for the loading machine and measuring equipment are as shown in Figure 2.

The overall longitudinal axial deformations of the specimens were obtained using the three linear variable differential transducers (LVDTs) located at the top part of the load cell machine, while another three LVDTs were attached at the centre of the specimens, measured the relative axial displacement over the 100 mm height of the specimens. The transverse deformations of the specimens were obtained using two LVDTs located at the centre of the specimens, diametrically wrapped a steel ties around the specimen. The overall concrete longitudinal strains were presented as the average value of LVDTs divided by the particular measured length.

The transverse deformations for concrete and steel strapping were obtained by using two sets of strain gauges located at the centre of the specimen in a diametrically direction. All the strains were measured using the data logger to record the values of load, displacement, and strain. Any cracking pattern, buckling, deformation, etc., were recorded during testing. The compressive strength of specimens was tested according to ASTM C39/C39M-11.

(a)

(b)

Figure 2 Diagram for (a) strain measuring equipment and (b) the loading device (TINIUS OLSEN Super "L" Universal Testing Machine)

2.3 Testing Load Patterns

Figure 3 illustrates the three testing load patterns implemented in this study, denoted as "M", "1C", and "3C". For testing load pattern "M", monotonically increasing displacement of rate 0.4 mm/min were executed on testing specimens until obvious strength dropped to more than 50% of the respective ultimate strength capacity, indicates the failure of the particular cylinder specimen. While load pattern "1C" describes an uniaxial single cyclic compression load involving unloading and reloading cycle with loading rate of 0.4 mm/min at several prescribed unloading stress values until the cylinder specimens failed. The cylinder specimen was loaded at a fixed load rate to a prescribed unloading stress value and then was unloaded to a target unloading level. After reaches the target unloading level (about 1 to 3 kN), the cylinder specimen was loaded again to the next higher prescribed unloading stress value for cyclic loading and so on, until the cylinder specimen failed. Three unloading and reloading cycles at each prescribed unloading stress value (denoted as "3C") was implemented to examine the effect of repeated loading history on SSTT confined cylinder specimens.

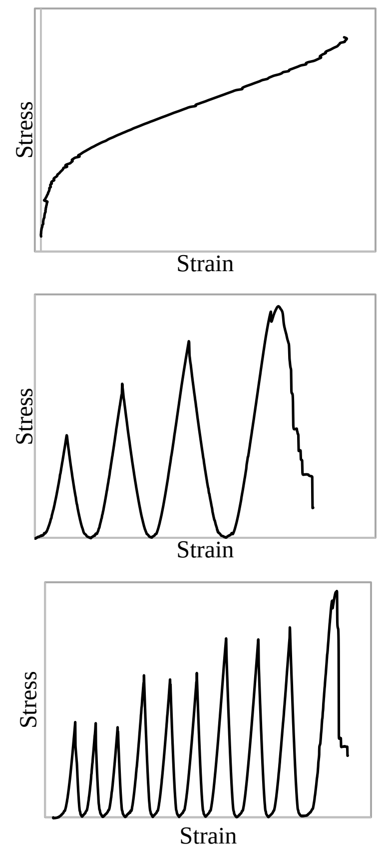


Figure 3 Loading patterns: "M": Uniaxial monotonic loading; "1C": Uniaxial single cycle loading at each prescribed load level; "3C": Uniaxial three cycles loading at each prescribed load level

3.0 TEST RESULTS

3.1 Envelope Curve

An envelope curve was defined by Sinha *et al*. as the curve joining the loading branches between each cycles and the uniaxial monotonic stress-strain curve estimated will falls on the envelope curves [11]. While Lam *et al*. [12] defined envelope curve as upper boundary response of unconfined and confined concrete subjected to any loading history in the stress-strain relationship. Throughout literature studies, there exists controversy regarding the crossing point between the envelope curve and uniaxial monotonic stress-strain curve. Some studies suggested that the uniaxial monotonic stress-strain curve should stay below the envelope curve [13, 14] while some studies suggested a coincidence between the uniaxial monotonic stress-strain curve and envelope curve [12, 15, 16]. As presented in Figure 4 and Figure 5, the uniaxial cyclic stress-strain curves of SSTT confined specimens are coincide together with the uniaxial monotonic stress-strain curve of the same cylinder specimens which tested with different load patterns, for both confining layers of steel straps (two layers and four layers). It is also observed that the envelope curves would probably stayed below the uniaxial monotonic stress-strain curves after reaching the ultimate compressive stress. Hence, this observation proved that the basic hypothesis of envelope curve is valid for SSTT confinement on high-strength concrete. The variation of confining layers and loading patterns does not have significant effect to this hypothesis, indicates the independency of envelope curve's validity to the confining layers and loading patterns.

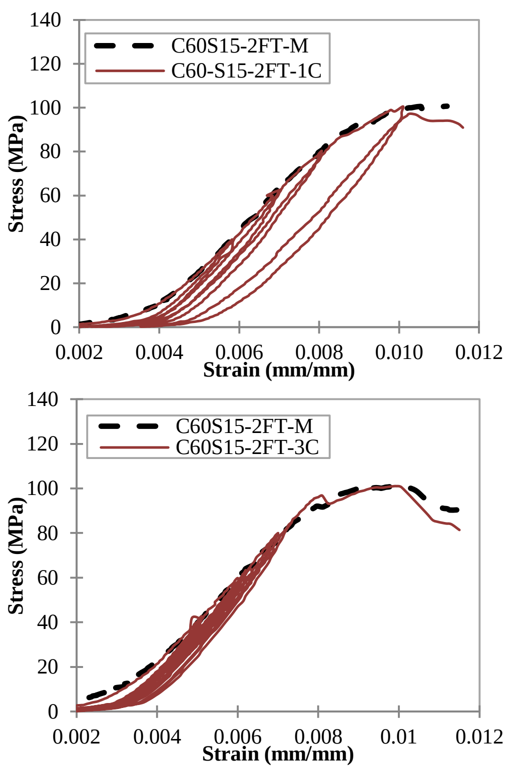


Figure 4 Uniaxial cyclic stress-strain curves of concrete confined with two layers of steel strapping in comparison with monotonic stress-strain curves of corresponding confined concrete

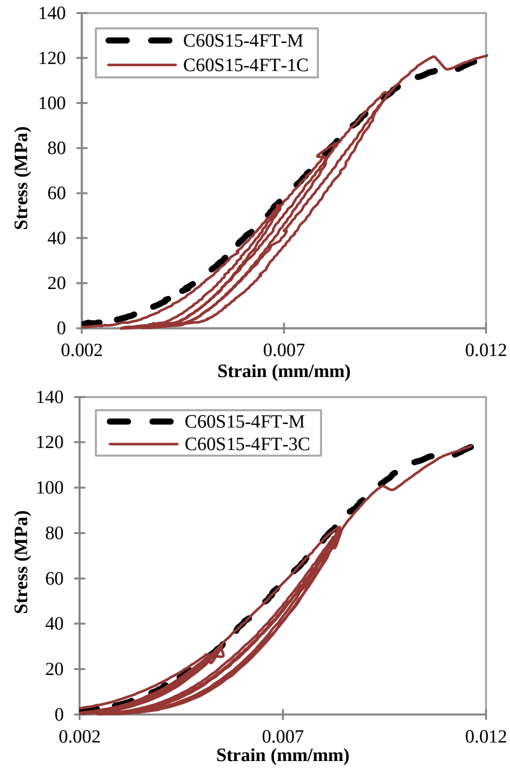


Figure 5 Uniaxial cyclic stress-strain curves of concrete confined with four layers of steel strapping in comparison with monotonic stress-strain curves of corresponding confined concrete

3.2 Plastic Strain

Plastic strain is defined as the concrete residual strain when it is unloaded to zero stress [12]. It is also been defined as non-recoverable residual longitudinal strain of each unloading cycle and the value will increase each time a load cycle was taken beyond the preceding cycle [14]. Existing studies e.g. FRP confinement [12,16,17] and tie reinforcement confinement [18] declared a linear relationship between the plastic strains of confined concrete and the axial strain at the starting point of unloading branches (also named as envelope unloading strain). Lam *et al*. [12] in their studies show that the plastic strain of FRP confinement under cyclic loading are linearly related to envelope unloading strain, and is independent of the amount of confinement. Figure 6 shows the relationship of plastic strain (ε_{pl}) versus envelope unloading strain ($\varepsilon_{un,env}$) for SSTT confinement with two and four layers of steel straps under uniaxial cyclic compression load. A linear relationship can be observed for both the SSTT confinement with two and four layers of steel straps and nevertheless, the linear trend lines coincide with each other, for $\varepsilon_{un,env} > 0.004$. This observation indicates that the plastic strain of SSTT confinement is independence of the amount of confining layers. A new model equation of plastic strain-envelope unloading strain can be developed, with correlation coefficient, R^2 equal to 0.77 as follows:

$$\varepsilon_{pl} = 0.46\varepsilon_{un,env} - 0.0006 \ , \varepsilon_{un,env} > 0.004 \qquad (1)$$

Four related existing plastic strain model equations proposed by different confinement methods has been listed in Table 3 to evaluate with current study. A comparison graph between the existing equations and present study's equation as proposed in eqn (1) is illustrated in Figure 7. It is surprisingly observed that SSTT confinement possess the lowest level of plastic strain comparing with others, indicates that such confinement with lateral pre-tensioning stress can minimize the strain deterioration during uniaxial cyclic compression load. This shows that SSTT confinement is suitable to be used in structure that experience repeating excitation, for example, earthquake.

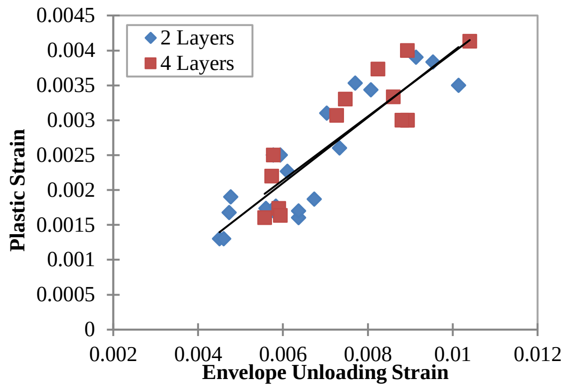


Figure 6 Plastic strain (ε_{pl}) versus envelope unloading strain ($\varepsilon_{un,env}$)

Table 3 The existing plastic strain models

Source	Plastic strain model
Abbasnia *et al.* [16]	$\varepsilon_{pl} = 0.4309\varepsilon_{un,env} - 0.0003$
Wang *et al.* [17]	$\varepsilon_{pl} = 0.815\varepsilon_{un,env} - 0.0020$
Lam *et al.* [12]	$\varepsilon_{pl} = 0.7160\varepsilon_{un,env} - 0.0016$
Sakai and Kawashima [18]	$\varepsilon_{pl} = 0.9600\varepsilon_{un,env} - 0.0023$

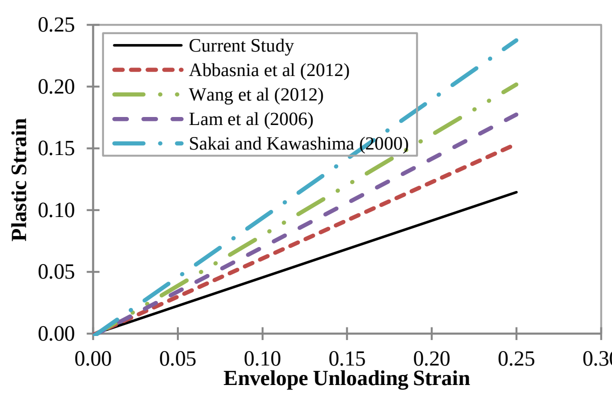


Figure 7 Comparison of existing plastic strain models with current study

3.3 Effect of Loading History

According to Sinha *et al*. [11], the reloading path of an unloading and reloading cycle in a loading history that crosses the unloading branch is named as "locus of common point". This uniqueness concept can be considered as stability limit where stresses applied at or below the locus of common point will having the same stress-strain responses without causing any further residual axial strains. The effect of loading history to the residual axial strains can be neglected in the unloading and reloading cycle. But, some research studies on FRP confinement [12, 16] do not agree with this uniqueness concept, where they experimentally proved the existence of residual axial strains under effect of loading history. A graph of increasing strain ratio (γ_n) versus number of cycles, n is presented in Figure 8 and Figure 9 for load patterns "1C" and "3C", where the increasing strain ratio is defined as follows:

$$\gamma_n = \frac{\varepsilon_{un} - \varepsilon_{pl.n}}{\varepsilon_{un} - \varepsilon_{pl,n-1}} \quad (2)$$

where $\varepsilon_{pl.n}$ and $\varepsilon_{pl,n-1}$ are the plastic strains of the nth and n-1th unloading/reloading cycle respectively. From the analysis, the increment (less than 1.0) and decrement (more than 1.0) of the strain ratio with the number of cycles indicates the invalidity of SSTT confinement to the uniqueness concept. When the confined cylinder specimens subjected to repeated cycles, the stress-strain response of the subsequent unloading and reloading cycles does not coincide but tends to shift to higher and lower axial strain side, indicating the cumulative effect of the loading history on the permanent strain.

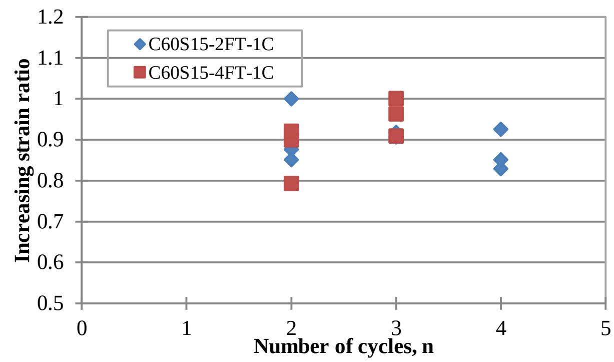


Figure 8 Increasing strain ratio, γ_n versus number of cycles, n for SSTT-confined specimens tested under uniaxial single cycles compression load

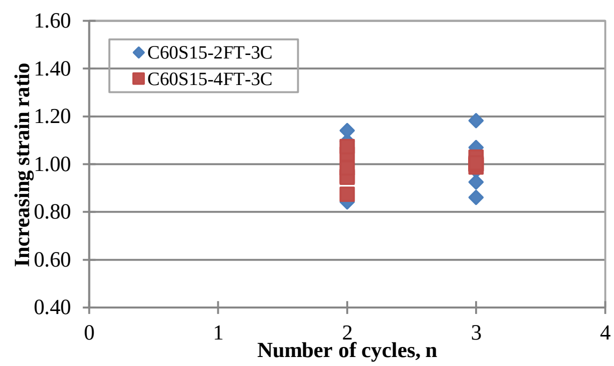


Figure 9 Increasing strain ratio, γ_n versus number of cycles, n for SSTT-confined specimens tested under uniaxial three cycles compression load

3.4 Effect of Confining Layers on Ultimate Strength

Figure 10 shows the graph of strength ratio versus confining ratio for SSTT confinement tested with uniaxial monotonic load. It should be noted that the confining ratio (x-axis) in the figure is referring to the effective mechanical volumetric ratio of steel confinement as per defined in Eurocode 8. The confining ratio for SSTT confinement with two layers of steel straps is 0.117 while for those with four layers of steel straps is 0.233. The results of the present study showed that the ultimate compressive strength of SSTT confinement increases with the increase of confining ratio, and about 112% of increment can be obtained for SSTT confinement with four layers of steel straps, 70% of increment for such confinement with two layers of steel straps.

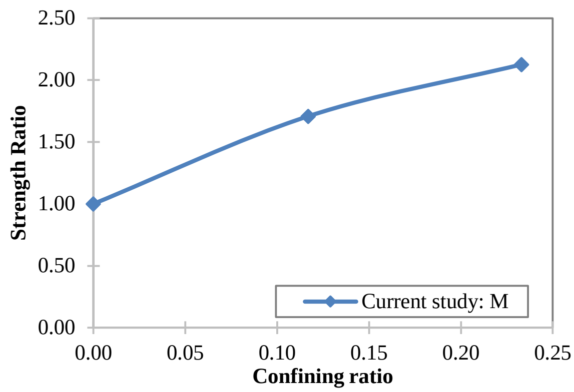


Figure 10 Graph of strength ratio versus confining ratio for load pattern "M"

3.5 Effect of Load Patterns on Ultimate Strength

As to investigate the loading patterns effect to the ultimate compressive strength of SSTT confinement, comparison chart of strength ratio versus confining ratio under the tested loading patterns is presented in Figure 11. The ultimate compressive strengths obtained for SSTT confinement under uniaxial monotonic load are used as datum of comparison for both confining ratios respectively (ratio 1.0). The result shows a minor reduction of ultimate strength of such confinement after underwent uniaxial cyclic loading (1C or 3C). Overall, the highest reduction of ultimate strength was just about 4% for the four layer steel straps confined specimens underwent uniaxial three cycles compression load (3C), while two layer steel straps confined specimens possess the lowest reduction in strength after cyclic loading. This shows that the effect of loading pattern do not have big influence to the ultimate compressive strength of SSTT confinement.

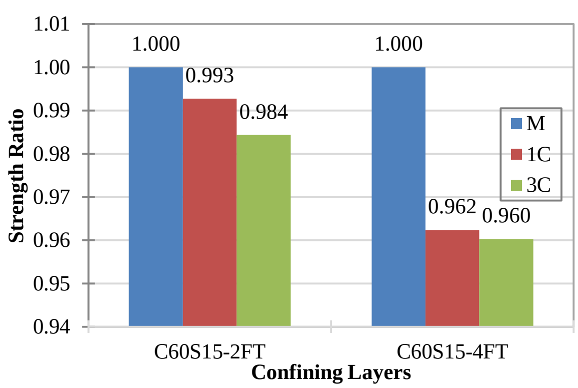


Figure 11 Comparison graph of strength ratio versus confining ratio under different load patterns

4.0 CONCLUSION

In this study a total of twenty-one SSTT confined cylinder specimens with different confining layers were tested under three different type of loading patterns and its cyclic responses were evaluated. Several observations can be obtained:

1. The stress-strain curves of SSTT confinement tested under uniaxial monotonic and cyclic compression load is the same, regardless of the effect of confining layers.
2. The relationship between the plastic strain and envelope unloading strain is linear and the confining layers do not have any significant effect on the plastic strain.
3. There is a cumulative effect on the permanent strain and stress deterioration under repeated unloading and reloading cycles for SSTT confinement and is proved invalid for the uniqueness concept of loading history.
4. SSTT confined cylinder specimens with more layers of steel straps give higher strength performance. However, the influence of maximum confinement layers in ultimate strength enhancement has not been studied in this research.
5. SSTT confinement do not possess significant effect on the ultimate strength reduction due to loading patterns (uniaxial monotonic and cyclic compression load).

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